ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Environmental Sciences 19 (2013) 654 – 662
Procedia Environmental Sciences

Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Soil chemical aspects of water management: modeling topsoil water, salt and sodicity dynamics

S.E.A.T.M. van der Zee*, S.H.H. Shah, and A. Leijnse[a]

[a]*Environmental Sciences Group, Ecohydrology, Wageningen University, P.O.Box 47, 6700 AA, Wageningen, Netherlands*

Abstract

In large areas worldwide, both in semi-arid and humid climates, the availability of good quality water for primary production in agriculture or natural vegetations is limited. Whereas soil and groundwater pollution are nowadays general problems, much larger areas have to deal with the hazards of soil and groundwater salinity. For soil types that are susceptible to physical degradation in view of their swelling and shrinking behaviour, also the salinity associated hazard of soil sodicity needs to be anticipated. Sodicity related soil physical degradation may be quite irreversible and is a major candidate for preventive rather than curative measures. The process of salt displacement has received much attention, and spatial variability has been given explicit attention by Dagan and Bresler (1979). Temporal variability of the boundary conditions has been investigated only recently, when both primary and secondary salinity were studied with so-called minimalist ecohydrological modelling (Suweis et al., 2010, Shah et al., 2011, Vervoort and Van der Zee, 2012). This work emphasized the atmospheric forcing of erratic rainfall on water and salt dynamics in the rootzone layer, either envisioned as a Poisson process, or with seasonal periodicity. Taking such erratic rainfall as well as spatial variability of the depth of the groundwater level into account, an impression can be obtained of the importance of different sources of variability. For our parameterization, we find that both spatial and temporal variability were responsible for the variation in root zone salinity, C, but that root zone sodicity, expressed with the Exchangeable Sodium Percentage, ESP, depends predominantly on spatial variability. The difference is understandable from the buffering mechanisms involved with C and ESP.

Selection and/or peer-review under responsibility of the Scientific Committee of the conference

Keywords: salinity;sSodicity; ESP; spatiotemporal variability; root zone model

* Corresponding author. Tel.:
E-mail address: sjoerd.vanderzee@wur.nl

Selection and/or peer-review under responsibility of the Scientific Committee of the Conference
doi:10.1016/j.proenv.2013.06.074

1. Introduction

In large areas worldwide, both in semi-arid and humid climates, the availability of good quality water for primary production in agriculture or natural vegetations is limited. Whereas soil and groundwater pollution are nowadays general problems, much larger areas have to deal with the hazards of soil and groundwater salinity. For soil types that are susceptible to physical degradation in view of their swelling and shrinking behaviour, also the salinity associated hazard of soil sodicity needs to be anticipated.

Soil salinity and sodicity problems are often referred to comprehensively as Salt Affected Soil issues and an extensive literature exists with regard to the physical, chemical, agronomic and plant physiological aspects of salts in the Soil Plant Atmosphere continuum. In this paper, we consider some recent advances of parsimonious modelling of SAS.

Nomenclature

C	concentration salt
Cz	concentration salt in groundwater
E	evapotranspiration rate
ESP	exchangeable sodium percentage
L	leaching/drainage rate
P	precipitation/rainfall rate
Rnet	net recharge rate
s	root zone water saturation
U	capillary upflow rate
Z	depth groundwater level
Zr	thickness rootzone
α	mean shower depth
λ	mean shower arrival rate

2. Spatial variability and salinity

The term salt affected soils refers to soils that are characterized by a poor balance with regard to easily soluble salts. Sometimes, a poor balance means that those salts (usually alkali and earth alkali chlorides, sulphates and bicarbonates) accumulate in large quantities (giving saline soils). Sometimes, salinity as such does not develop, but the balance between the divalent cations Ca^{2+} and Mg^{2+} on one hand and Na^{+} on the other hand is upset by enrichment of sodium. In that case, we speak of sodic soils or alkali soils. If both salinity and sodicity occur simultaneously, we have saline-sodic soils. For an overview of different types (and additional ones) of SAS, we refer to Szabolcs (1989). The interest for SAS derives from the adverse effects of salinity on primary production (agronomic yield) and soil structure degradation.

Research of soil salinity has received much attention over the past century (Oster and Jayawardana, 1998). A milestone in the research of SAS is the report by Richards et al. (1954), as it defined so many different aspects related with salt affected soils. Despite its discussion of simple model approaches such as the Leaching Requirement (Corwin et al., 2007), that addresses how much should be irrigated to avoid salinity to grow larger than a designated level, this report is quite conceptually and experimentally inclined. Another milestone is the work by Maas and Hoffman (1977) that considers how primary production, through its almost 1:1 relationship with transpiration by plants and crops, is adversely affected by the salt concentration. This paper is still a major reference for appreciating the impact of salinity on water availability for crops and vegetations.

Sodicity (often quantified by ESP, the Exchangeable Sodium Percentage, which is a measure of the fraction of the cation exchange complex occupied by sodium) related soil physical degradation may be quite irreversible and is a major candidate for preventive rather than curative measures (Bresler et al., 1982, Bolt, 1982). Whereas the physical processes of increasing salinity and sodicity have been considered with models of different complexity (Bolt, 1982, Russo and Bresler, 1977a,b), the full complexity has been investigated seldomly. This statement refers to the negative impact of a decrease of salinity in a sodic soil on the hydraulic properties of swelling/shrinking soil. This physical feedback has received relatively little attention to our best knowledge. An example where the feedback of salt concentration and ESP on the hydraulic conductivity has been considered is the UNSATCHEM model (Simunek et al., 1996), that provided a salinity-sodicity focussed 1D numerical model. Experimentally, Ezlit (2009) investigated the functions K(C, ESP) incorporated in this model in more detail, where K stands for hydraulic conductivity.

A major advance in water flow and solute transport modelling has been the recognition that spatial variability at the field scale deserves explicit attention. Early milestones in this advance were papers by Bresler and Dagan (1979) and Dagan and Bresler (1979) that were focussed on the transport of nonreactive salts in heterogeneous soils. This work according to the parallel stream tube model approach inspired many groups worldwide . Both the flow and transport were investigated from the perspective of salinity and theoretically by Russo and co-workers, whereas Jury (1983), Destouni (1991) and Van der Zee and Riemsdijk (1987) considered various complications such as non-equilibrium and chemical interactions.

In the past decade, a new, parsimonious approach to flow has been introduced for root zone flow dynamics, that uses, similarly as Dagan and Bresler (1979) a minimalist model approach. In this research, a 0D rootzone is modelled, and a major complication is the assumption of erratic rainfall that is commonly approximated as a Poisson process (Rodriguez-Iturbe and Porporato, 2004). Hence, in this approach, the temporal rather than the spatial variability of Dagan and Bresler (1979) is emphasized and the local problem has been simplified from one-dimensional to zero-dimensional. The strength of this approach is that complex forcing by rainfall can be dealt with, at the expense of spatial variability.

Scope of this paper is focussed on salinity dynamics, particularly with regard to erratic rainfall, using the ecohydrological framework for erratic weather. In a, yet, simple way, also spatial variability is taken into consideration. An impression is given of the practical perspective of this approach to salt affected soil research.

3. Methodology

The basis of our methodology is that we consider a root zone that communicates with atmosphere, groundwater, and is subject to erratic rainfall. Hence, major fluxes of water concern precipitation (P), evapotranspiration (E), drainage (or leaching, L) and capillary upflow (U). The last three are determined by the wetness of the root zone soil similar as in the concepts of Feddes et al. (1978), Rodriguez-Iturbe and Porporato (2004), and Vervoort and Van der Zee (2008). This leads to a water balance, and if groundwater is to some degree saline, a salt balance. These balances are coupled, as import of salts into the rootzone by U has effects on E and L (Suweis et al., 2010, Shah et al., 2011).

In addition, if sodicity is also taken into consideration, another balance needs to be coupled with those of water and salts, i.e., reflecting the composition of salts. The composition is usually dominated with anions that reveal limited sorption and therefore may be dealt with as 'inert salt' and cations. As was already mentioned, the cations may be divalent (Ca, Mg, behaving to some extent similar) and monovalent (Na). Physical degradation may occur if the ratio of Na over divalent cations becomes too large. As the adsorbed/exchanged pool is much larger than the dissolved one, in most soils, the ratio for the cation exchange complex is most important. For this reason, sodicity is expressed with ESP where the fraction Na is given by adsorbed Na over the cation exchange capacity. Usually, sodicity induced degradation problems occur if ESP becomes larger than say 15%.

Due to the erratic weather, where rainfall is a Poisson process in the cases of Suweis et al., 2010, Shah et al., 2011), the developing salinity of the root zone is also erratic. The coupled balances can be solved numerically, which despite the simple situation can be quite cpu-intensive. For this reason, we simplified the impact of spatial variability to an illustrative case only. To consider spatial variability, similar as Bresler and Dagan (1979), several parameters are appropriate candidates. For instance, the spatial variability of the hydraulic parameters has been well documented, but this is also the case for rainfall intensity, root zone thickness (Zr), and phreatic water depth (Z). As the phreatic water level varies gently, whereas soil surface and root zone thickness may vary more irregularly, we considered spatial variability of the distance between root zone basis en groundwater level: Z-Zr. This variability may be conceived as due to an undulating soil surface, or systematic changes in the depth of the phreatic level going from the hydrological divide towards streams.

Results and Discussion

We assumed that the depths of the phreatic level is on average 200 cm, and normally distributed with a standard deviation of 43 cm. Groundwater salt concentration (Cz), and calcium are 0.02 molc/L and 0.05, respectively. Due to the erratic weather, where rainfall is a Poisson process and climate is dry ($\alpha\lambda$=0.33 cm/day, see Vervoort and Van der Zee, 2012), the initially fresh rootzone salinizes and becomes sodic. At the long term, the erratic patterns of water saturation, concentration and ESP stabilize, and it becomes appropriate to characterize these variates with their time-averaged probability density function, pdf. For six realizations, these pdfs are shown in Figure 1.

The pdfs shown in Figure 1 concern the mean groundwater level and five larger values and from our earlier work, we know that at groundwater levels of 200 cm depth, there is a shift in regimes: for shallower groundwater, it dominates the root zone salinity, for deeper groundwater, rainfall dominates (Shah et al., 2011, Vervoort and van der Zee, 2012).

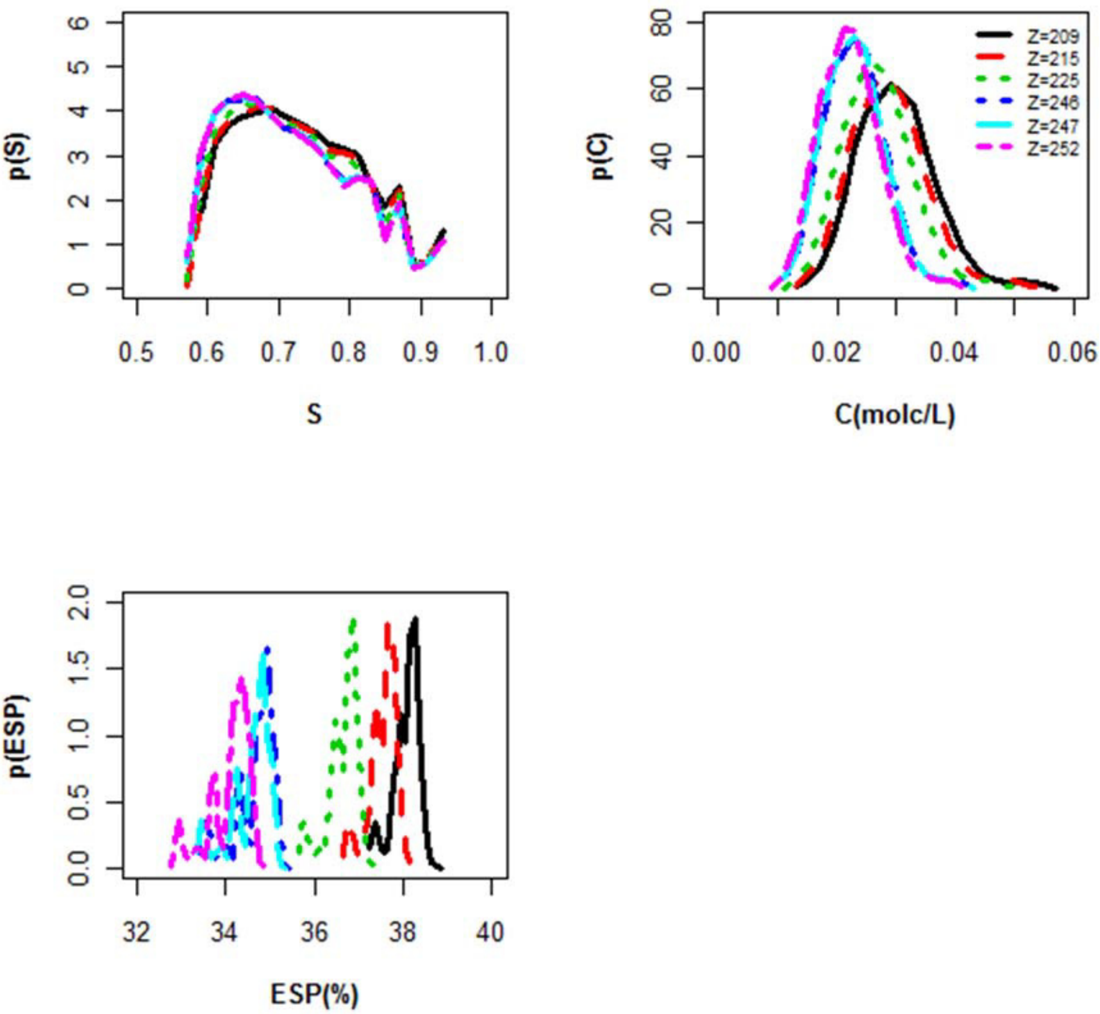

Figure 1: Probability density functions for root zone saturation (s), salt concentration (C) and sodicity (ESP), averaged for the last 50 simulated years. *Result*s for six groundwater levels deeper than the average of 200 cm.

Also, our earlier investigations demonstrated by Shah et al. (2011), that the pdf(s), of water saturation, is affected by the osmotic effect of salt concentrations when these exceed say 0.02 molc/L, because the osmotic pressure decreases evapotranspiration and leaching losses. In Figure 1, this effect is hardly visible, but it becomes more distinct for shallower groundwater. Compared with Shah et al. (2011), the soil is wetter but the salt concentration is very comparable, despite that the root zone thickness here is 25 cm instead of 100 cm as in their case.

Also shown in Figure 1 are the pdfs of the exchangeable sodium percentage ESP, which appear to be quite narrow: the pdfs for different groundwater levels are well separated. The reason is that ESP is chemically buffered by the exchange at the solid surface, which attenuates the fluctuations due to erratic weather. Remarkable is also that the pdfs for ESP become more dispersed as the groundwater level is deeper, and as the pdfs for Z of 246-252 cm reveal, they also become more erratic (e.g. with multiple peaks). This is the result of sorption buffering too. Different from the case of salinity (represented here by the concentration of salts, C), in the case of ESP the storage does not only concern the liquid volume in the root zone. Rather, the storage of cations is controlled by the storage of dissolved mass in the root zone water volume plus the adsorbed mass that is associated to the solid surface. Generally, the adsorbed mass is larger than that in the liquid phase, leading to retardation factors well above unity. Accordingly, the ESP grows towards its final value much slower than salinity (C). How fast it grows, depends also on the water fluxes in and out of the rootzone.

In Figure 2, we show how the different fluxes depend on the depth of the groundwater level. It is clear that the main fluxes are the net infiltration recharge by rainfall (Rnet) and the evapotranspiration (ET), as they are two to five times larger than the other two (capillary upflow, U, and drainage or leaching, L). The reason that net infiltration increases as Z increases, is that for deeper groundwater, the root zone has less replenishment from groundwater, is somewhat drier, and less prone to incidental surface runoff. The slightly drier soil, averaged over the last 50 simulated years, may also lead to a decrease of evapotranspiration and drainage as Z increases. A large decrease is found for the capillary upflow, which becomes four times smaller as Z increases from 120 cm to 250 cm. Accordingly, as groundwater is deeper, the upward movement of salts is much slower and a long term averaged steady state, where the ESP has stabilized to an average value, with incidental, annual transitions to larger or smaller values, has not yet been attained.

Whereas Figure 2 indicates gradual changes in the water fluxes as a function of groundwater level, it also indicates clear trends that are also apparent in Figure 1. To appreciate the impact of spatial variability should be done on the basis of dissolved salt mass in the root zone in the case of salinity. However, it is clear that in view of the considerable width of the pdfs of concentration, C, the contributions of both spatial and temporal variability of salinity are comparable, and the mean and standard deviation of C are about 0.032 and 0.009 molc/L, assuming normality, i.e. a variation coefficient of 0.28.

For ESP, each pdf has a limited width, but the spatial effect is much more distinct. Averaging ESP over the entire ensemble of different Z-values that range according to a normal distribution of $Z=200\pm34$ cm leads to an average of ESP=38 %, and a standard deviation of about 3%, giving a variation coefficient of merely 0.08. Though this variation is far smaller than that for the concentration, it is almost purely due to the spatial variability, and not caused by the temporal fluctuations, as the fluctuations in time of ESP have already been shown to be minor. A cautioning remark is that for larger Z-values, the ESP may not yet have attained a long term equilibrium. This aspect has been ignored in this paper, so more demanding (longer) simulations may lead to a somewhat larger ESP variation coefficient. The different impacts of spatial and temporal variability, for the present case with respect to ground water depth and rainfall (or irrigation) input, suggests that analyses of ESP development may be reasonably well approximated with averaged boundary conditions. What has not been investigated yet is whether or not ‘averaged boundary conditions’ result in similar long term ESP and concentration levels and how to average in the first place. Also, it is clear that besides ground water depth, other factors such as the hydraulic conductivity, may have to be taken into account.

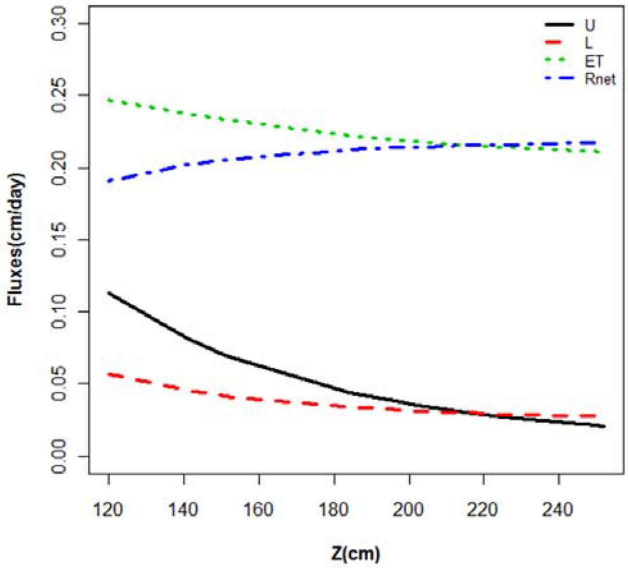

Figure 2: Magnitude of the fluxes as a function of depth of the groundwater level.

4. Conclusions

In this paper, we considered the impact of the depth of the groundwater level on the salinity and sodicity that develop in a root zone that initially was neither saline, nor sodic. We have seen that salinity and sodicity depend differently on spatiotemporal variability. Whereas salinity is about equally affected by the spatial and temporal sources of variability that were assumed here, this is not the case for sodicity. Sodicity appears to be predominantly affected by spatial variability.

These results are partly corroborated by observations in the field. Seasonal salt blooms were observed in e.g. S. Spain, whereas for sodicity, such short term periodic behaviour has not been reported to our best knowledge. In practice, the difference in how spatial variability affects salinity and sodicity may be reflected differences in the patchiness of saline or non-saline topsoils, and sodic or non-sodic topsoils. Possibly, in the latter case, horizontal interactions need to be taken into account also, for a proper assessment.

The modelling of this paper has been done with a mixed root zone model, that involves a number of quite restrictive assumptions. The soil layer between the root zone and groundwater has been assumed to be always in steady state. Drained water immediately enters the groundwater, and capillary upflowing water likewise enters the root zone. The time scales that would be involved in that flow may be of similar order of magnitude as required for salinity build up in the root zone. However, this error may be quite modest, compared with the ignored impact of either positive or negative recharge on the groundwater level. The assumption of a perfectly mixed root zone, in the present case of 25 cm thick, seems quite appropriate for the water and salt balances, particularly if an agronomic situation is being modelled. However for the case of sodicity, this approximation may be more debatable. Due to the physical feedback of sodicity on the soil structure, notably the hydraulic functions, profound layering may occur in reality.

Although the mixed root zone model approach may be challenged, the major assumptions may be hidden in the parameterization of our, and similar, models. For instance, both the water uptake reduction in case of drought and of salt stress is commonly modelled with very similar functions (Maas and Hoffman, 1977, Feddes et al., 1974). These functions are attractive for the way they reflect complicated processes, as they integrate properties of the climate, plant, and soil. However, this makes the parameterization highly site specific. Due to all the complexity underlying these processes, there are no obvious ways of generalizing them to other conditions. That the functions and their parameterization are generalized nevertheless, may have a larger impact than assuming a root zone to be perfecly mixed.

Acknowledgements

This research has been funded by the Dutch research program Knowledge for Climate.

References

[1] Bolt GH. *Soil Chemistry*, Elsevier Scientific Publishing Company, Amsterdam; . (2nd Edition), 1982.

[2] Bresler E, Dagan G. Solute dispersion in unsaturated heterogeneous soil at field scale: II. Applications, *Soil Sci.Soc. Am. J.* 1979;**43**:467-472.

[3] Bresler E, MacNeal BL, Carter DL. Saline and sodic soils: Principles-Dynamics-Modeling, Springer-Verlag, Berlin/Heidelberg/New York; 1982, p.236.

[3] Corwin DL, Rhoades JD, Simunek J. Leaching requirement for soil salinity control: steady-state versus transient models. *Agricultural Water Management,* 2007;**90**:165-180.

[4] Dagan G, Bresler E. Solute dispersion in unsaturated heterogeneous soil at field scale: I. Theory, *Soil Sci. Soc. Am. J.* 1979;**43**:461-467.

[5] Destouni G. Prediction uncertainty in solute flux through heterogeneous soil. *Water Resourc. Res*. 1992;**28**:793-801.

[6] Ezlit YD. *Modelling the Change in Conductivity of Soil Associated with the Application of Saline –Sodic Water*. PhD Thesis, Faculty of Engineering and Surveying, University Of Southern Queensland, Australia; 2009.

[7] Feddes RA, Bresler E, Neuman SP. Field test of a modified numerical model for water uptake by root systems. *Water Resour. Res.* 1974;**10**:1199-1206.

[8] Maas EV, Hoffman GJ. Crop salt tolerance - current assessment. *J. Irrig. Drain*. Div. Proc. Am. Soc. Civil Eng. 1977;**103**:115-134.

[9] Oster JD, Jayawardane NS. Agricultural management of sodic soils. In *Sodic Soil: Distribution, Management and Environmental Consequences.* (eds) Sumner ME, Naidu R. Oxford University Press NY;1998; p.126–147.

[10] R Development Core Team. *A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria 2011. ISBN 3-900051-07-0, URL http://www.R-project.org/.

[11] Richards LA, Allison LE, Bernstein L, Bower CA, Brown JW, Fireman M, Hatcher JT, Hayward HE, Pearson GA, Reeve RC, Wilcox LV. *Diagnosis and Improvement of Saline and Alkali Soils*. U.S. Dept. Agr. Handbook No. 60, U.S. Govt. Printing Office, Washington D.C;1954, p. 160

[12] Rodriguez-Iturbe I, Porporato A. Ecohydrology of water-controlled ecosystems: soil moisture and plant dynamics, *Cambridge University Press*, Cambridge, UK. 2004.

[13] Russo D, Bresler E. Effect of mixed Na/Ca solutions on the hydraulic properties of unsaturated soils. *Soil Sci. Soc. Am. J.* 1977a;**41**:713-717.

(14] Russo D, Bresler E. Analysis of the saturated-unsaturated hydraulic conductivity in a mixed Na/Ca soil system. *Soil Sci. Soc. Am. J.* 1977b;**41**:706-710.

[16] Simunek J, Suarez DL, Sejna M. The UNSATCHEM software package for simulating one-dimensional variably saturated water flow, heat transport, carbon dioxide production and transport, and solute transport with major ion equilibrium and kinetic chemistry, version 2. *USDA-ARS, U.S. Salinity Laboratory*, Riverside, CA. Res. Report No. 141, p. 186.1996.

[17] Suweis S, Rinaldo A, Van der Zee SEATM, Maritan A, Porporato A. Stochastic modeling of soil salinity. *Geophysical Research Letters* 2010;**37**:L07404, doi:10.1029/2010GL042495.

[18] Szabolcs I. *Salt Affected Soils*. CRC Press Inc., Boca Raton, Florida; 1989,p. 274.

[19] Van der Zee SEATM, van Riemsdijk WH. Transport of reactive solute in spatially variable soil systems. *Water Resour. Res.* 1987;**23**:2059-2069.

[20] Vervoort RW, van der Zee SEATM. Simulating the effect of capillary flux on the soil water balance in a stochastic ecohydrological framework. *Water Resources Research,* 2008;**44**:W08425.